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ENERGY DOUBLER DIPOLE VENT LINE SYSTEM

PREPARED UNDER FERMILAB SUBCONTRACT NO. 92690
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FOR

FERMI NATIONAL ACCELERATOR LABORATORY
BATAVIA, ILLINOIS

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A. Introduction

In a telephone conversation on 4/3/78, M. Kuchnir described the energy doubler dipole vent system. It appears that this system is as shown in Figure 1:

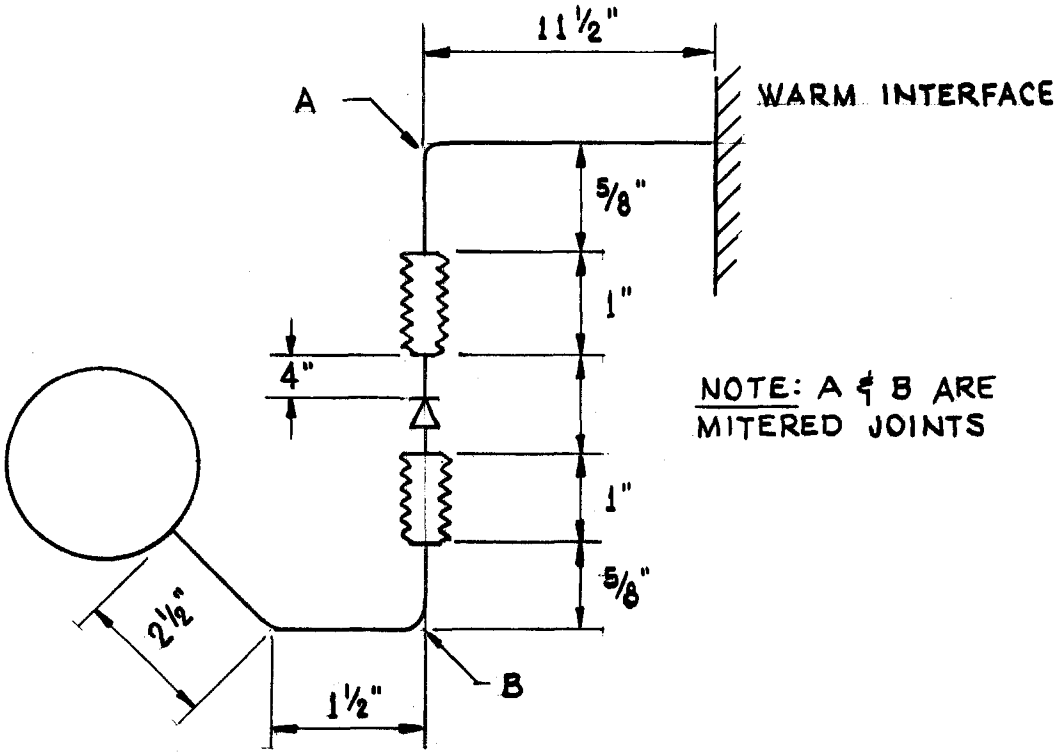

FIGURE 1

The vent line consists of a 1 in. OD, .049 in. wall tube (stainless steel). The bellows are 1 in. ID, 1-1/2 in. OD. The cold check valve is a ball valve with a .9 in. Ø seal (.45 in. long). The ball is located in a cage of 1.64 in. diameter and can travel   . The ball is restrained from traveling all the way by a wire or similar device. If this wire were to break, the ball would backseat on the discharge opening and block the vent line.

Each magnet has one vent line. There is one safety lead for four dipole magnets and a quadrupole. Inductance of the quadrupole is .038 Henry. At 4,500 A, stored energy is 385,000 joules.

M. Kuchnir indicated that there are some data on the performance of the electrical heater, wound in with the superconductor, as follows:

a) The heater is "kicked" by discharging a capacitor. This discharge provides 200 joules to 80 ft of conductor or at least deposits this energy in the vicinity of 80 ft of conductor.

b) With 3,000 A of current flow the measured voltage across the superconductor is 4.8 V. This occurs 40 msec after the heater has been kicked.

c) Voltage after 80 msec is 24. It is anticipated that at least 160 ft of conductor is normal at this time.

The present dipole magnet design has the following volumes for liquid and gaseous helium, vacuum and liquid nitrogen:

Single-phase Space:	30.5 liters
Two-phase Space:	7.1 liters
Liquid Nitrogen on Shield:	6.7 liters
Beam Tube (Vacuum):	23.8 liters
Insulating Vacuum:	66.9 liters

B. Consider Various Cases

1. Energy Taken up by Liquid Helium as a Function of Constant Specific Volume (no venting) and Pressure:

TABLE I

P, atm	1.6	2.0	3.0	4.0	5.0	6.0
T, °K	4.5	-	4.7	5.09	5.34	5.6
V_s, cc/gr	8.21	8.21	8.21	8.21	8.21	8.21
M, gr	3,715	3,715	3,715	3,715	3,715	3,715
I, joules	9.87	-	10.10	11.36	12.01	12.71
ΔM, gr	0	0	0	0	0	0
ΔI, joules	0	-	855	5535	7950	10551

Depending on rate of heat transfer, we can reach a pressure of 6 atm probably in a matter of 100 to 200 msec. The question then is, at what rate do we have to accelerate fluid into the vent line to maintain pressure in the cryostat.

2. Vent Line Considerations:

The vent line will see high velocities of a fluid which is above the critical pressure and is single-phase. The temperature and density of the fluid is governed by the condition of fluid closest to the inlet of the vent line. Initially, in the first couple of hundred msec, the fluid will be compressed liquid.

The vent line has four points of high impedance. These are:

-Inlet from cryostat. Pressure drop is at least 1-1/2 x $1/2 \rho v^2$.

-Two mitered joints. Pressure drop is at least 1-1/2 x $1/2 \rho v^2$.

-Ball check valve. Pressure drop is at least 1/2 x $1/2 \rho v^2$.

Minimum pressure drop of the vent line up to its penetration through the vacuum jacket is then 3-1/2 x $1/2 \rho v^2$. The area of the vent line is some 4.1 cm^2. Table II shows the data:

TABLE II

Density of fluid initially in vent line is .125 g/cc.

Velocity of sound at 4.75°K and 4 atm is approx. 20,000 cm/sec.

Velocity (cm/sec)	2,000	4,000	6,000	8,000
3-1/2 x $1/2 \rho v^2$ (atm)	.875	3.5	7.875	12.25
Mass Flow Rate (g/sec)	1025	2050	3075	4100

The pressure required to accelerate the fluid from zero velocity to high velocity is not very high, because the mass present in the vent line is small. For instance, accelerating a mass of 5 grams (40 cc) present in the vent line at time t = 0 to a velocity of 4,000 cm/sec in .1 sec requires a force of 200 grams. This force is exerted over a surface area of 4 cm^2. Equivalent pressure is then 50 g/cm^2 = .7 psig.

Steady state pressure drop in the line may be calculated assuming an equivalent line length of 26 in. plus seven times the length of the bellows. Total length is then of the order of 40 in.

Mass flow rate at a velocity of 2,000 cm/sec is:

$$G = \frac{1025 \times 3600}{454 \times 4.1} \times 930 = 1.84 \times 10^6 \text{ lb/hr ft}^2$$

$$\text{At } T = 4.75°K$$

$$P = 4 \text{ atm}$$

$$\mu = 85 \times 10^{-4} \text{ lb/ft hr}$$

$$Re = 1.64 \times 10^7$$

$$f = \frac{.046}{Re^{.2}} = .00166$$

$$\rho = 7.8 \text{ lb/cft}$$

$$\frac{\Delta P}{L} = \frac{.00166 \times (511)^2}{193 \times 7.8 \times .91} = .32 \text{ psig/ft}$$

$$\text{For } L = 4 \text{ ft}$$

$$\Delta P = 1.25 \text{ psig}$$

3. Required Rate of Venting as a Function of Heat Input to the Liquid:

Assume that the magnet reservoir is at 4 atm and kept at this level during the venting operation. Table III provides the data. Table III indicates that the helium in the magnet cryostat can take up large amounts of heat. However, the model assumed for the generation of Table III is possibly incorrect. It assumes that all of the liquid in the cryostat warms up uniformly.

TABLE III

Temp. °K	Spec. Vol. V_s cc/gr	Mass gr	ΔM gr	Enthalpy J/gr	ΔEnthalpy Joules
5.09	8.21	3715	-0-	14.69	-0-
5.2	8.42	3622	93	15.41	2641
5.3	8.63	3534	181	16.07	5003
5.4	8.86	3442	273	16.78	7480
5.5	9.14	3337	378	17.56	10124
5.6	9.48	3217	498	18.44	13018
5.7	9.91	3078	637	19.44	16166
5.8	10.45	2919	796	20.62	19704
5.9	11.17	2731	984	22.01	23632
6.0	12.11	2519	1194	23.63	27885
6.5	18.19	1677	2038	31.86	45189
7.0	23.44	1301	2414	37.67	53839
7.5	27.86	1095	2620	42.24	59313
8.0	31.79	959	2756	46.21	63389

C. Events of First 100 Msec

Most probably very incomplete mixing occurs initially. For instance, all of the liquid in the ends of the cryostat will not participate in the heat transfer and will be expelled as cold liquid. Liquid located between the stainless steel bands receives heat very slowly, except in the small area adjacent to the heated windings of the magnet. Also, there is no force driving out this liquid. It may, therefore, stay in place for a reasonably long period of time (seconds) and not require a lot of extra space.

A more realistic model may be as follows: Assume that only 5% of the helium present in the cryostat participates in the heating process and that the rest of the liquid is in zones where no heating occurs. This model is probably more correct for the first hundred msec, after quench initiation. The energy required to reach 3 atm without venting may be estimated as follows:

Compress .95 x 30.5 = 28.975 liters from 1.6 to 3.0 atm without adding heat.

Initial Condition		Final Condition	
P =	1.6 atm	P =	3.0 atm
T =	4.5°K	T =	4.68°K
H =	11.20 J/gr	H =	12.40 J/gr
V_s =	8.21 cc/gr	V_s =	7.985 cc/gr
S =	3.683 J/g °K	S =	3.683 J/g °K

The new volume of the 28.975 liters of non-heated liquid is now:

$$\frac{7.985}{8.21} \times 28.975 = 28.181 \text{ liters}$$

The heated liquid volume, initially at 1.525 liters, now becomes 2.319 liters. This then results in a specific volume of:

$$\frac{2.319}{1.525} \times 8.21 = 12.49 \text{ cc/gr}$$

At 3 atm, temperature of this fluid is 5.56°K and the internal energy is 17.60 J/gr. Total heat added to this mass is:

$$(17.60 - 9.87) \frac{1.525}{8.21} = 1{,}436 \text{ joules}$$

Dr. Fowler indicated that with the heater embedded in the coil, ultimately 50 lb of the conductor (15% of the total coil) will participate primârily in the heating process. This part of the total coil has a surface area interface of approximately 4,500 cm^2 with the liquid helium. Heat added through this surface area will affect only a small depth of the liquid (say .020 in. = .05 cm). The volume of this liquid is then of the order of 225 cc (27.5 gr).

The heat transfer coefficient at low flow rates is of the order of .017 W/cm^2 °K. With a temperature difference of 30°K, we can transfer heat at the rate of .500 W/cm^2. In 10 msec we will supply some 4500 x .05 = 225 joules to the liquid or 8 joules per gram. This then will convert this liquid into a two-phase mixture of approximately 50% quality and rapidly superheat the mixture. Flow direction of this mixture is away from the heated zone, resulting in an insulated area where the helium gas temperature follows the heated conductor temperature.

The effects of the heating process are probably different in the channels between shells from those in the area between bore tube and inner shell. The main difference is direction of flow away from the conductor. In the .021 in. wide slot between shells, flow of heated fluid is directed along the windings of the inner shell. Acceleration of the fluid will not require much pressure because the column to be accelerated is short (a few cm). A force of 2 psig will provide an acceleration force of some 500 g's. Liquid will travel 6 cm in 5 msec. However, after a few msec, velocity is high and friction becomes a factor. It appears then that in a few msec the liquid may be cleared out of the narrow channel and that it will be replaced with a mass roughly five times smaller (gas versus liquid). Heat required to warm this mass per cm^2 of conductor surface area (facing the helium) from 4.8°K (boiling point) to 7.5°K is approximately .030 joules. This heat may be supplied in a period of some 20-30 msec. In the process of warming to 7.5°K the volume of the gas increases by a factor 2.5. This means that in 20-30 msec 2.5 windings see warm gas and receive heat from this gas.

Based on the above, it seems reasonable to expect that in some short period of less than 50 msec from initiation of quench, additional turns adjacent to the heated turn have gone normal.

Figure 2 shows the general area of normal turns, assuming that the heated turns are located in shell 2 at points X. The rate at which helium needs to be removed from the cryostat will be governed by the total area available for heat transfer. Figure 2 shows a surface area A of some 3,600 cm^2 which will transfer heat to the liquid helium. The rate of heating is governed by film boiling coefficients. Rates will range from 1 to 10 W/cm^2.[1] Total rate heat transferred to the helium will probably be of the order of 35-70 kW over a period of a few sec until the bulk of the helium has been removed from the space between bore tube and inner shell. The question then is whether the liquid in that space can be removed in a sec or less without exceeding the pressure rating of the vessel.

Volume in the space is approximately 3,000 cc and mass is initially of the order of 400 grams. Essentially all of this fluid needs to be expelled in less than half a sec in order to maintain a constant pressure in this zone. The fluid will be expelled into the end zones of

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1. Advances in Cryogenic Engineering, Vol. 10, Section M-U, p. 325.

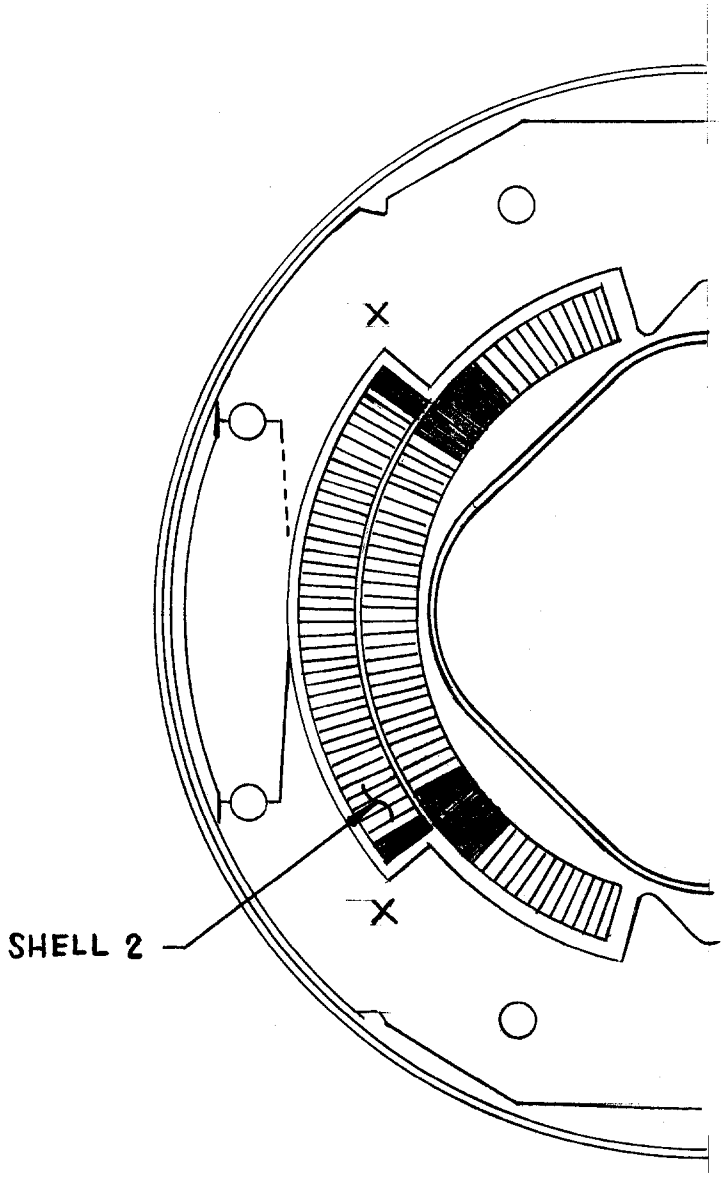

FIGURE 2

the magnet, flowing away from the center of the magnet. Some mixing will take place. Complete mixing would provide the data of Table III. Flow rate from the magnet cryostat then would have to be of the order of 1,500 gr/sec. Table II indicates that pressure drop in the vent line caused by velocity heads would be of the order of 1.5 to 2 atm, when liquid flows through the line. Gas at 7°K or warmer will triple this pressure drop.

D. Modifications to the Vent System

1. At this time only modifications external to the cryostat are contemplated. It is obviously necessary to make the pressure drop in the vent system external to the magnet zero. This can be approached by dumping the helium into a large diameter tube of short length, equipped with a relief plate of large flow area. Consider a 6 in. diameter plate which can lift 3/4 in. Flow area is then of the order of 14 sq in. Velocity through this area is then (1,500 g/sec at 7°K) some 1,500 cm/sec. The equivalent velocity head is only .15 psig. It is necessary to remove the seating force from the valve or plate, since under steady state conditions it holds against 20 or 25 psig. A negative seating force may be obtained with the arrangement of Figure 3.

2. The previous discussions leads one to believe that the existing internal vent system of the magnet is too small to provide adequate relief for the cryostat. It is very likely that the massive heat flux achieved from uniform quenching and adding 500,000 joules to the magnet system will result in the collapse of the bore tube.

3. To prevent collapse of the bore tube, one might try to add helium gas to this tube at the onset of the quench. This also unfortunately adds a lot of heat to the liquid helium in the channel between bore tube and first shell and will defeat the purpose of the gas addition.

4. For experiments in the B-12 facility, solely carried out for the testing of the quench with heaters, it might be possible to protect the bore tube from collapsing by insertion of a heavy-walled pipe which touches or nearly touches the four flat sides of the bore tube. In that case, the pressure in the cryostat could rise to 200-220 psig (15 atm) without rupturing the cryostat vessel and the liquid in the cryostat could take up 60,000 to 70,000 joules, while venting at the same rate as previously (without heater induced quench). It is not clear whether

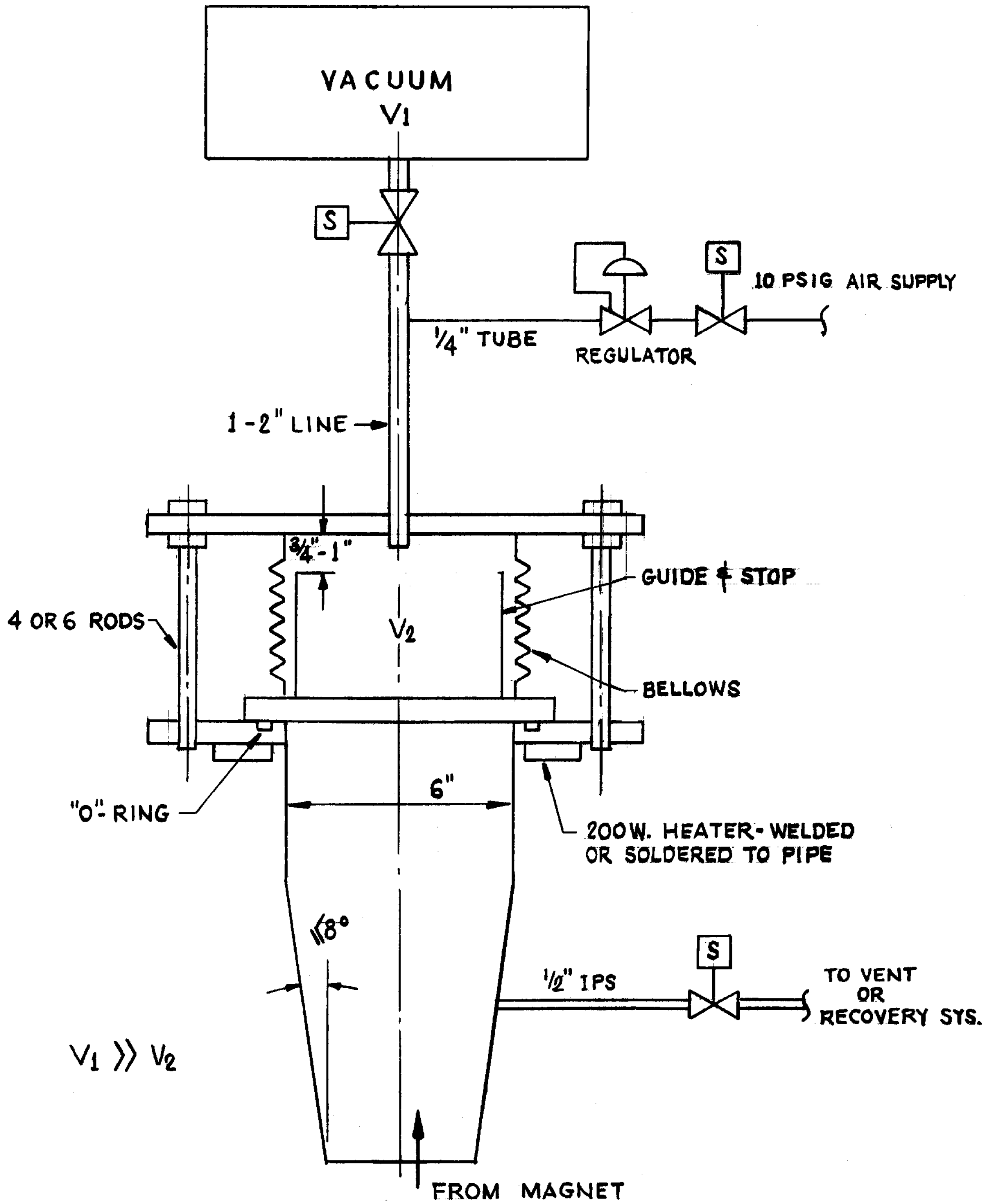
VACUUM
V1
S
S
10 PSIG AIR SUPPLY
1/4" TUBE
REGULATOR
1-2" LINE
3/4"-1"
GUIDE & STOP
4 OR 6 RODS
V2
BELLOWS
"O"-RING
6"
200W. HEATER-WELDED
OR SOLDERED TO PIPE
8°
S
1/2" IPS
TO VENT
OR
RECOVERY SYS.
V1 >> V2
FROM MAGNET

FIGURE 3

the bellows in the vent line and magnet to magnet connections are adequate to handle these pressures. Also, it is not clear whether the check valve in the vent line is designed to withstand the higher velocities and increased pressure differences.

E. Conclusions

At this time, it appears difficult to predict the effect of the heater on the venting requirements of the magnet cryostat. The most important question to answer is, whether liquid removed from the heat zones can transmit heat to other windings in the process of flowing by these windings. To obtain a feel for the problem, one might start from the premise that the cryostat is venting at a high rate after some 50-100 msec and calculate heat transfer coefficients between the inner shell and the helium flowing between inner shell and bore tube.

The area for flow is approximately 1 sq in. Coefficients for various flow rates as required to eject liquid and gaseous helium from the cryostat may be calculated. Assume that the pressure in the cryostat is 4 atm. Table IV shows the rates of heat transfer between helium and inner shell as a function of flow rate. Temperature difference between superconductor and helium is assumed to be 1°K.

TABLE IV

Flow Rate, g/sec	50	100	200	400
G, lb/hr ft^2	5709	11420	22837	45674
T, °K	5.6	5.6	5.6	5.6
μ, lb/ft hr	.0080			
ρ, lb/cft				
C_p, Btu/lb °R	2.22			
Re	14867	29734	59468	118937
j	.00336	.00293	.00255	.00222
Pr	1.25			
$Pr^{2/3}$	1.16			
h, Btu/hr ft^2 °F	36	64	112	194
ΔT °R	1.8			
Q/A W/cm^2	.021	.036	.057	.110

The superconductor in heat transfer with the helium has a weight of 5 gr per cm^2. The amounts of heat required to drive up the temperature of the superconductor are shown in Table V:

TABLE V

Temp., °K	4	6	8	10
ΔH, joules/cm^2	-0-	.0015	.005	.011

It turns out that 1.5 millijoules/cm^2 will drive the conductor normal. If the mass flow rate passing the conductor is the equivalent of venting at the rate of 100 g/sec, then the conductor may reach 6°K in some 50 msec, if the fluid flowing by the conductor is at least 7°K. A large part of the helium flowing through the channel will be cold. However, helium flowing by the hot conductors will warm up and this heated fluid will expand in a circumferential direction around the bore tube on its way to the vent line. If warm, it will drive other conductors normal.

It may be stated that if helium can drive parts of the conductor normal in the first half sec, the vent line system will be too small and the cryostat will be subjected to a large pressure rise. The bore tube will collapse, unless supported as suggested.